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DESCRIPTION OF AN OPERATIONAL TOOL FOR DETERMINING GLOBAL SOLAR RADIATION AT GROUND USING GEOSTATIONARY SATELLITE IMAGES

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Abstract—An operational tool for the fine-scale mapping of the incident solar radiation at ground is presented. This tool called "Heliosat station" makes use of image acquired in the visible spectral range by meteorological geostationary satellite to produce accurate maps of global radiation. Satellite data are directly received at ground by a cheap HF receiver and processed by a personal computer IBM-PC compatible using the already known Heliosat method. This method has been successfully tested during 30 consecutive months beginning January 1983. The first prototype of the Heliosat station was realized in 1985. Now a Heliosat station is routinely operated by *Agence Française pour la Maîtrise de l'Energie* since January 1987 for mapping solar radiation over Europe.

1. INTRODUCTION

The density of the radiation measurement network at ground level in well-covered countries is still low, and the average distance between stations is around 150 to 200 km. This is not sufficiently refined to take into account smaller scale variations which are important for the use of solar energy. In other parts of the world, the networks are even more sparse, particularly in countries such as Africa where solar energy is sorely needed.

On the other hand, meteorological geostationary satellites provide images of cloud fields over the whole surface of the Earth, usually in two spectral ranges: the visible; and the thermal infrared, with a ground resolution of 1 km to 10 km depending on the instrument and the latitude of measurement. The time interval of these observations varies between 30 minutes and 3 hours.

Proper processing of these satellite data provides a wealth of information useful in the production of solar atlases, particularly for those areas where no traditional observations are available. But these satellite data also make it possible to investigate spatially small-scale variations of available solar energy, knowledge of which is needed for planning purposes.

A great number of studies clearly demonstrate that satellite data can be used successfully for mapping both the global radiation at ground level and the cloud coverage over very large areas such as continents, with spatial resolution of about 5 to 30 km, and with an accuracy better than 10% of the incident radiation (Cano *et al.*[1], Diabaté *et al.*[4], Gautier *et al.*[6], Grüter *et al.*[7], Michaud–Regas[9], Möser and Raschke[10] and [11], Tarpley[13]).

This research phase has been followed by an operational one for the routine production of global radiation maps or derived data (cloud coverage, albedo) throughout the world. The first effort reported was by Gautier *et al.*[6] who mapped the hourly global irradiation during three months. Now many works are in progress for much longer periods. For example, the *Centre de Télédétection et d'Analyse des Milieux Naturels (CTAMN) de l'Ecole Nationale Supérieure des Mines de Paris (ENSMP)* and the French Meteorological Office undertook their routine in 1983, and the German Meteorological Office in 1984.

However such routines are mostly operated within meteorological organizations with large computing means; and in our opinion, they are not suitable for use and operation by the people involved in the solar energy business. One of the purposes of the Heliosat Program of CTAMN/ENSMP was to define an operational tool for routine production of radiation maps to fill up this gap. Since it has been shown (Grüter *et al.*[7], Cano *et al.*[1]) that besides their use in solar climatology such maps are of great interest in various domains ranging from solar building architecture to agroclimatology, some specifications were drawn to meet these goals. This tool much be cheap, very simple, easy to use and to maintain. It also must comprise a direct reception for Earth observing geostationary satellites (Meteosat, GMS, GOES). The conversion of satellite data into global radiation maps must be accurate. It must only require satellite data and must not demand too much computing-time. This real-time system must also provide some capacities in image processing color display and printouts.

This tool has been realized and is now commercially available. It is called the Heliosat station. After careful examination of the published methods for the processing of the satellite data, the method of Cano *et al.*[1] was chosen and slightly modified to become the Heliosat method (Diabaté *et al.*[4], Moussu *et al.*[12]). Technical review of the widespread hardware (reception system, computer, graphics means) and of their cost both in purchase and in maintenance was made to select the components of the system.

Therefore the Heliosat station comprises

- a software to convert satellite data into maps of global radiation
- a software providing some features in image processing
- a HF receiver with antenna to receive analog satellite data (WEFAX format)
- a personal computer (PC) IBM compatible
- a satellite signal digitizing board to be installed into the PC
- a PC graphic board to display color maps.

These components are now briefly described taking into account that only the software and the digitizing board were designed by CTAMN.

2. DESCRIPTION OF THE HELIOSAT METHOD

The Heliosat method has been already described (Diabaté *et al.*[4], Moussu *et al.*[12]), and here is only provided a short description of it.

The basic remote sensing data are taken from any geostationary satellite observations within the visible spectral range. Once received and stored onto the computer harddisk, a satellite image is preprocessed using geometric correction with landmark correlation, noise filtering, and normalization of digital counts by the spectrally integrated solar irradiance which would be measured by the sensor after it has been reflected on a horizontal plane located at each pixel under clear sky. This normalization is detailed in Moussu *et al.*[12] and is similar to the computation of the albedo, either of the ground or of clouds if any are present (apparent albedo).

The basic idea of the method is that the amount of the cloud cover over a given area statistically determines the global radiation for that area. Thus the processing is divided into two steps. A cloud cover index is derived for each location or pixel (i,j) of the original satellite image and subsequently used in a second step for a statistical estimation of the global radiation (Fig. 1).

The occurrence of a cloud in the field of view of the satellite sensor will result in an increase of the apparent albedo. Therefore the amount of the cloud coverage per pixel is provided by the following quantity called cloud index:

$$n^t(i,j) = (\rho^t(i,j) - \rho(i,j))/(\rho_c - \rho(i,j))$$

where

$\rho^t(i,j)$ is the apparent albedo at pixel (i,j) and at instant t,
$\rho(i,j)$ is the ground albedo,
ρ_c is the mean value of the maxima of the albedo values for cloud,
$n^t(i,j)$ is the cloud index at pixel (i,j) and at instant t.

The construction of the ground albedo map follows the two-step procedure described by Moussu *et al.*[12]. Briefly speaking the first step consists both in the detection of clouds and in the determination of the ground albedo using an iterative filtering applied to a time-series of images. This provides a map of ground albedo if every pixel is cloud-free at least one time. This step is done only once. The second step takes into account the seasonal variations of the albedo, and the ground albedo map is updated during the routine processing by weight averaging the instantaneous apparent albedo for a cloud-free pixel with the previously determined ground albedo at this pixel.

However it is also possible using the CARTO-PC image processing software to make use of a map of ground albedo provided by external sources. The geometry of this map must be adapted to the geometry of the satellite scene. Also the albedo must be linearly fitted to the count dynamics provided by the ensemble antenna-HF receiver-A/D converter.

The computation of ρ_c is performed using the same time-series of images. At each cloudy pixel, only the maximum value of the albedo within the time-series is retained. Then a histogram of these maxima is constructed and the modal value is taken as ρ_c. Periodical examinations of this value show that ρ_c may be considered as a constant for given satellite imagery.

The Heliosat method does not perform properly when the ground albedo is close to the albedo of the clouds. It is specifically the case in snowy areas. Here, the use of an alternate cloud index defined with the radiance measured by the satellite in the thermal infrared spectral band has been proposed (Cano *et al.*[1]) but is not implemented at that moment within the Heliosat method.

Using about 32 months of data, Cano *et al.*[1], Diabaté *et al.*[4], Michaud-Regas[9] showed that this cloud cover index is linearly related to the total atmospheric transmission factor $K(i,j)$, which is defined as the ratio of global radiation at ground on a horizontal surface $G(i,j)$ to the horizontal irradiance outside the atmosphere $G_o(ij)$:

$$K(i,j) = G(i,j)/G_o(i,j)$$

and

$$K^t(i,j) = a(i,j)\, n^t(i,j) + b(i,j)$$

with $a(i,j) < 0$, i.e., low values of n correspond to high values of K.

In agreement with the general knowledge of solar radiation, this relationship is restricted to solar elevations greater than 12° and to satellite elevations greater than 5°. It follows that this method cannot operate optimally for latitudes greater than about 60°.

Diabaté *et al.*[4] and Michaud–Regas[9] closely examined the variations of the parameters a and b both in time and space. Using 30 months of data over France, they found that for the same hour (UT), keeping the same set of parameters (a,b) throughout the year and also constant in space gives only a slight increase (about 1%) in the retrieval error. Therefore

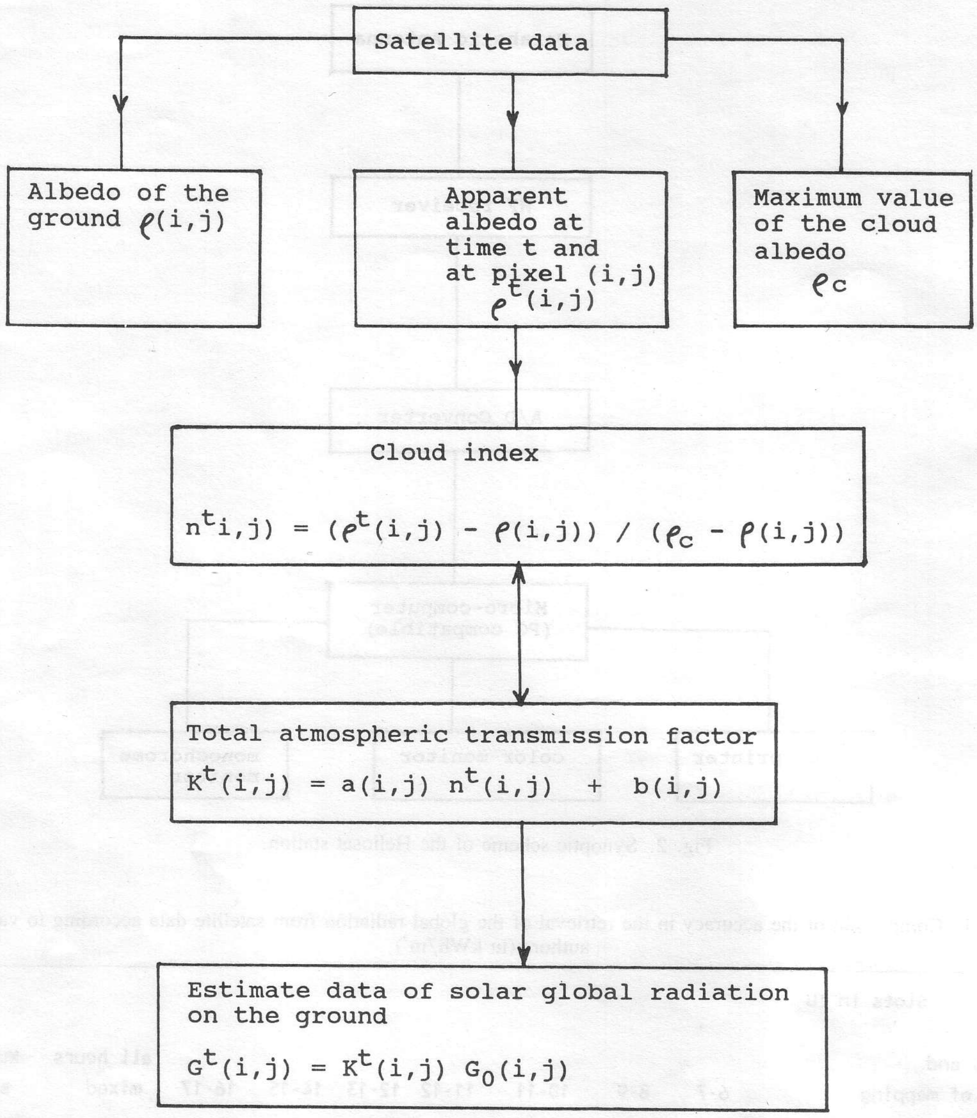

Fig. 1. Synoptic scheme of the Heliosat method.

it was concluded that Heliosat should only contain one set of parameters (a,b) per processed hour. Furthermore comparisons have been made between the method of Möser and Raschke[10,11], which ranks also as one the most accurate of similar methods, and the Heliosat method for Western Central Africa in June 1984 (Stulhmann, personal communication). Radiation maps provided by the Heliosat method were computed using the hourly parameters sets derived for Europe. The discrepancy of the estimates of the monthly mean of the daily global radiation between both methods presents a r.m.s. of 250 Wh/m^2 and is 40% less than the discrepancy between the estimates of the Möser and Raschke model and coincident pyranometers.

Also work in progress at *École des Mines* shows that the solar elevation influences the parameter a and that, if corrected, the value of a is unique throughout the day without an increase of the error. As for b, this parameter describes the atmosphere for very clear sky and subsequently depends upon the turbidity of the atmosphere. However this problem is expected to be solved at the end of the year 1988.

3. DESCRIPTION OF THE COMPONENTS OF THE HELIOSTAT STATION

The Heliosat station is composed of software and hardware. Besides the algorithms for the conversion of satellite data into global radiation, the software performs automatically the following operations: storage of data onto the harddisk; contrast enhancement and false colors display; accurate navigation; and noise filtering. In a standard fashion, three images are processed a day, each giving a map of the hourly global radiation. Once the last hourly map is produced, the daily global radiation is computed and displayed. At the end of each month, the above quantities are time-averaged per pixel. These monthly

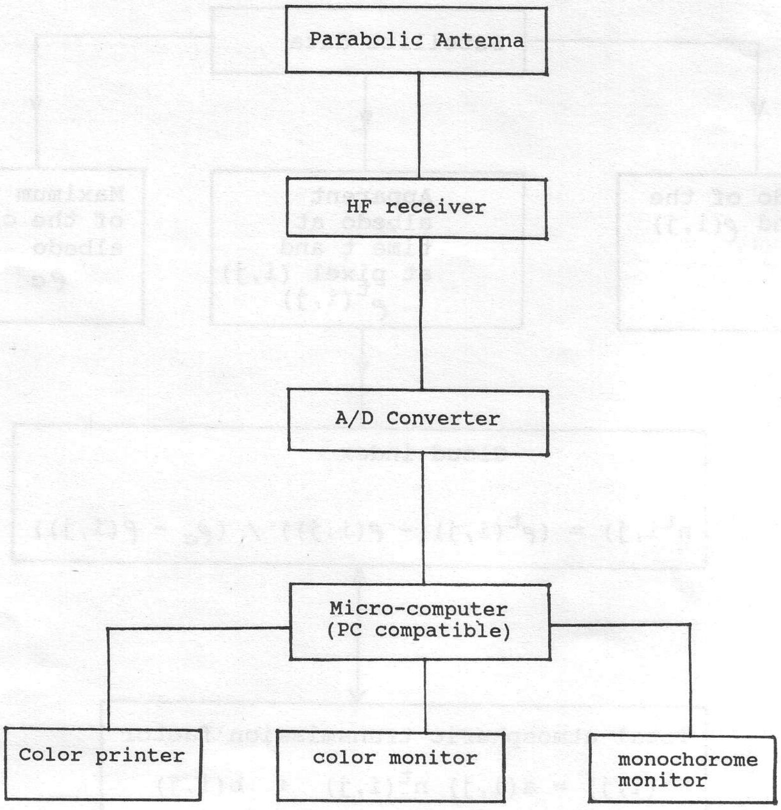

Fig. 2. Synoptic scheme of the Heliosat station.

Table 1. Comparison of the accuracy in the retrieval of the global radiation from satellite data according to various authors (in kWh/m²)

Authors and period of mapping		Slots in TU 6-7	8-9	10-11	11-12	12-13	14-15	16-17	all hours mixed	Number of stations
Möser and Raschke in [7]	June 1979	0,04	0,07	0,09	-	0,09	0,07	0,05	-	23
	Apr. 1982		0,06	-	0,08	-	0,06	-	-	80
Cano et al.[1]	May 1979	-	-	-				-	0,12	27
	April 1982	-	0,06	-	0,07	-	0,05	-		80
Reinhardt and Schwarzmann in [7]	April 1982	-	0,01	-	0,13	-	0,10	-	-	80
Dedieu et al.[2]					0,12	-	-	-	-	
Marullo and Viola[8] (method of Gautier)	18/7/83				-	-	-		0,07	1

means are displayed and saved both for archiving and for further processing.

The number of scenes processed a day (3) was only dictated by the dissemination schedule of visible data covering all of Europe, and provided by the Meteosat satellite. Since the greater the number of hourly radiation maps the more accurate the retrieval of the daily radiation, this number is subject to change depending upon the geographical area, the dissemination schedule, the geostationary satellite, and at last by the processing time.

The Heliosat software presents also some features the user may select at his will: display any of the images stored on the disk, choose the slots of acquisition, and extract some statistics for any location present in any of the images (global radiation and albedo are mostly used).

The image files provided by the Heliosat station follow the CARTO-PC standard. Therefore any Heliosat image can be processed using this performant image processing software. This allows the user to undertake successfully any particular task making use of Heliosat images while still having a general and flexible system. Comparisons of radiation maps to other maps or digital cartography into specific geometrical projections are examples of such particular purposes.

Briefly described, the hardware of the Heliosat station is a satellite data receiver with antenna and a personal computer IBM-PC compatible with digitizing and graphic boards. A color printer may be added (Fig. 2). The satellite receiver is of analog type and allows the decoding of the so-called *WEFAX* (*WE*ather *FACS*imile) format emitted by the meteorological geostationary satellites observing the Earth. Such receivers are made by numerous producers and are well-distributed throughout the world. They are cheap and maintenance-free.

The personal computer is connected to the receiver through a analog–digital converter especially designed for this purpose. This board decodes the analog signal coming from the satellite in the WEFAX format. The signal is digitized using eight bits, then handled by the converter to the personal computer (PC). While the PC processor is writing a line of the image onto the harddisk, the converter is processing the following line. The use of this board is not restricted to the Heliosat method. It is now mainly used with the "Wefaxsat" software of Ecole des Mines de Paris for meteorological forecasting or educational purposes and is available as a commercial product independently of the Heliosat software.

Any limited area located within one of the standard satellite emitted windows may be selected. Software also supports the various resolutions at ground provided by the diverse satellite radiometers.

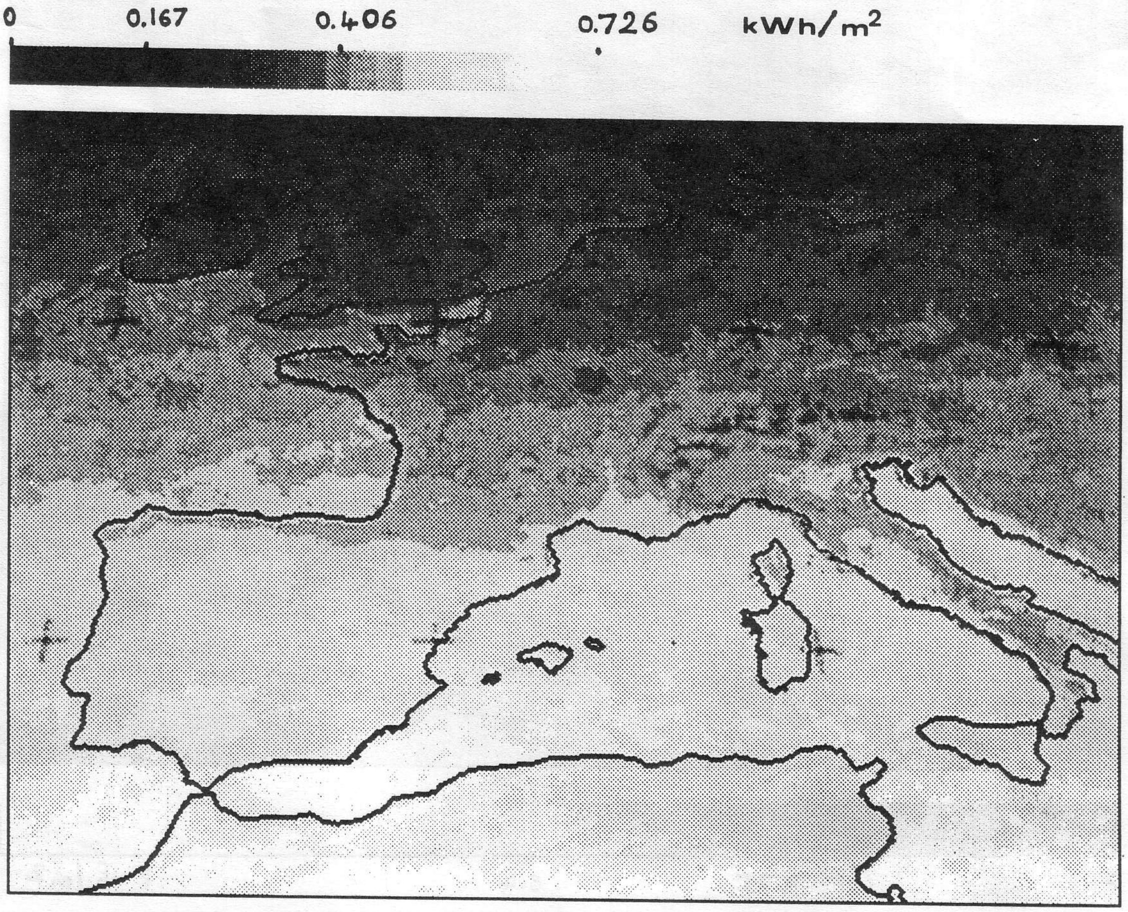

Fig. 3. Map of the hourly global radiation observed between 12 and 13h *UT* and averaged over the year 1983 for Europe. Radiation increases from black to white.

Once the image is fully received and stored onto the harddisk, it is displayed, after contrast enhancement, onto a color screen using a graphic board. Various graphic standards are supported by the Heliosat software: Matrox PIP 1024, Number Nine 8 bits, Adage PG 90/10, Truevision Targa 16, IBM PGA, IBM MCGA for PS 30, Tecmar Graphics Master, at the moment of the writing.

4. DISCUSSION

The various components of the Heliosat station have been carefully tested.

A routine was undertaken in January 1983 to check the validity and the accuracy of the Heliosat method (Demarcq[3]). It ended in August 1985, 32 months later. The comparison of the predicted global radiation versus the observed radiation for 30 ground stations demonstrates that the r.m.s. error in the reconstruction of both the instantaneous hourly global radiation G_h and the monthly average of G_h is less than 0.06 kWh/m^2 (Diabaté *et al.*[4], Michaud–Regas[9]). Table 1 compares the accuracy obtained by various authors in the reconstruction of the instantaneous hourly radiation from satellite data. Some of the published results cannot be compared to the others because of their nature or of the units they are expressed in (Gautier *et al.*[6], Tarpley[13]). This table demonstrates that the method of Cano *et al.*[1],

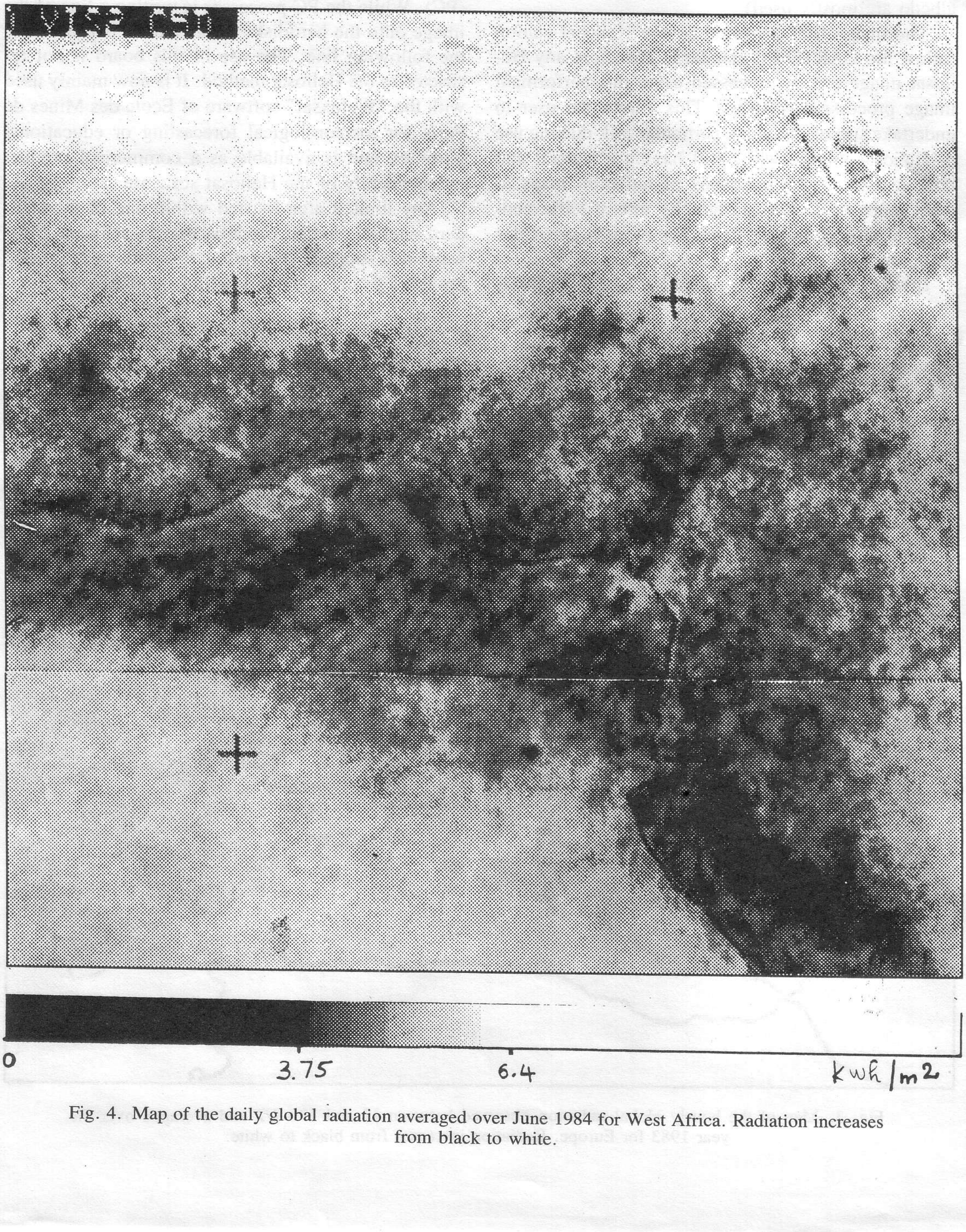

Fig. 4. Map of the daily global radiation averaged over June 1984 for West Africa. Radiation increases from black to white.

from which the Heliosat method originated, ranks as one of the most accurate.

The Heliosat station as described above exists at CTAMN since August 1985 and a copy of it was delivered to Agence Française pour la Maîtrise de l'Energie which operates it since January 1987 for the mapping of the radiation over Europe. Examples of the maps it supplies are presented in Figures 3 and 4.

The production of an hourly global radiation map requires about 100 minutes for a PC-XT, and 60 minutes are needed for the daily map. Processing hourly maps to obtain monthly means takes about 5 minutes. These times are only indicative and depend strongly upon the hardware used as the processors are becoming more and more performant. For example, times must be divided by at least a factor of 3 if one uses a PC-AT.

The Heliosat station brings an up-to-date scientific method to the end users in the field of solar energy. It is cheap and needs no maintenance. It is an open system in the sense that it may be tailored to the particular needs of the users. Engineers appreciate the detailed maps of global radiation it gives to evaluate the dimensioning of solar buildings. Furthermore derived products such as albedo maps are of great interest for climatologists or for vegetation studies (Diabaté *et al.*[5], Moussu *et al.*[12]).

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